Le hasard fait bien les choses

Corinne Touati

Inria

Janvier 2013
Definition (Roger Myerson, "Game Theory, Analysis of Conflicts")

“Game theory can be defined as the study of mathematical models of conflict and cooperation between intelligent rational decision-makers. Game theory provides general mathematical techniques for analyzing situations in which two or more individuals make decisions that will influence one another’s welfare.”

- Branch of optimization
- Multiple actors with different objectives
- Actors interact with each other's
Example

- 2 boxers fighting.
- Each of them bet $1 million.
- Whoever wins the game gets all the money...

Question: **Elements of the Game**

- What are the player actions and strategies?
- What are the players corresponding payoffs?
- What are the possible outputs of the game?
- What are the players set of information?
- How long does a game last?
- Are there chance moves?
- Are the players rational?
Game Theory and Nobel Prices in Economy

- Alvin Roth (2012, 1951) – experimental GT
- Lloyd Shapley (2012, 1923) – fair sharing, potential games
- Roger B. Myerson (2007, 1951) – eq. in dynamic games
- Eric S. Maskin (2007, 1950) – mechanism design
- Thomas C. Schelling (2005, 1921) – bargaining
- Reinhard Selten (1994, 1930) – Subgame perf. eq., bounded rationality
- Kenneth J. Arrow (1972, 1921) – Impossibility theorem

(Jorgen Weibull - Chairman 2004-2007)

(more info on http://lcm.csa.iisc.ernet.in/gametheory/nobel.html)
Example of successful applications

Economy:
▶ Pricing mechanisms
▶ Auctions

Politics:
▶ Fight against terrorism
▶ Negotiation and dispute resolution, bargaining
▶ Effect of electoral rules to politicians’ strategies

Biology:
▶ Cancer cells propagation
▶ Genetics and population evolution

And many others:
▶ Evolutionary psychology (social sciences)
▶ Intellectual right properties (law)
▶ Policy responses to global warming and climate change...
La théorie des jeux et les systèmes (informatiques) distribués

- Rien à voir avec les jeux vidéos
Rien à voir avec les jeux vidéos

Les protagonistes ne sont pas des humains: téléphones, ordinateurs...

Popularité croissante dans les grands systèmes distribués depuis les années 90 du fait de:
- L'augmentation du nombre des protagonistes
- L'accroissement et la complexification des systèmes
- La dynamité

⇒ on a besoin de méthodes automatisées pour concevoir, gérer les systèmes et évaluer les performances
La théorie des jeux et les systèmes (informatiques) distribués

▶ Rien à voir avec les jeux vidéos
▶ Les protagonistes ne sont pas des humains: téléphones, ordinateurs...

Popularité croissante dans les grands systèmes distribués depuis les années 90 du fait de:

▶ L’augmentation du nombre des protagonistes
▶ L’accroissement et la complexification des systèmes
▶ La dynamicité
La théorie des jeux et les systèmes (informatiques) distribués

▶ Rien à voir avec les jeux vidéos
▶ Les protagonistes ne sont pas des humains: téléphones, ordinateurs...

Popularité croissante dans les grands systèmes distribués depuis les années 90 du fait de:
▶ L’augmentation du nombre des protagonistes
▶ L’accroissement et la complexification des systèmes
▶ La dynamicité

⇒ on a besoin de méthodes automatisées pour concevoir, gérer les systèmes et évaluer les performances
Outline

1. Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2. Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3. Conclusion
Outline

1 Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3 Conclusion
The Prisoner Dilemma

<table>
<thead>
<tr>
<th>A stays Silent</th>
<th>Prisoner B stays Silent</th>
<th>Prisoner B Betrays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Each serves 6 months</td>
<td>Prisoner A: 10 years  \ Prisoner B: goes free</td>
</tr>
<tr>
<td>A Betrays</td>
<td>Prisoner A goes free</td>
<td>Each serves 5 years  \ Prisoner B: 10 years</td>
</tr>
</tbody>
</table>

What is the best interest of each prisoner?

What is the output (Nash Equilibrium) of the game?
The Prisoner Dilemma - Cost Space

What are the optimal points?

What is the equilibrium?

Cost for Prisoner A

(S,S) (S,B) (B,S) (B,B)

Cost for Prisoner B

(B,S) (B,B) (S,B) (S,S)
The Prisoner Dilemma - Cost Space

Optimal points
Equilibrium Point
(S,S) (S,B) (B,S)
(B,B)

Cost for Prisoner B
Cost for Prisoner A

What are the optimal points?
What is the equilibrium?
**Definition: (Finite or Matrix) Game.**

- \( N \) players, finite number of actions
- Payoffs of players (depend on each other actions and) are real valued
- Stable points are called Nash Equilibria

**Definition: Nash Equilibrium.**

In a NE, no player has incentive to unilaterally modify his strategy.

\[ s^* \text{ is a Nash equilibrium iff:} \]

\[ \forall p, \forall s_p, u_p(s_1^*, \ldots, s_p^*, \ldots, s_n^*) \geq u_p(s_1^*, \ldots, s_{p-1}^*, s_p, \ldots, s_n^*) \]

In a compact form:

\[ \forall p, \forall s_p, u_p(s_{-p}^*, s_p^*) \geq u_p(s_{-p}^*, s_p) \]
Nash Equilibrium: Examples

Find the Nash equilibria of these games (with pure strategies)

**The prisoner dilemma**

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>
Find the Nash equilibria of these games (with pure strategies)

### The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ not efficient

### Battle of the sexes

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>
Nash Equilibrium: Examples

Find the Nash equilibria of these games (with pure strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>
⇒ not efficient

Battle of the sexes

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>
⇒ not unique
Nash Equilibrium: Examples

Find the Nash equilibria of these games (with pure strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>
⇒ not efficient

Battle of the sexes

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>
⇒ not unique

Rock-Scisor-Paper

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
</tr>
<tr>
<td>P</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
</tr>
<tr>
<td>R</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
</tr>
<tr>
<td>S</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
</tr>
</tbody>
</table>
Nash Equilibrium: Examples

Find the Nash equilibria of these games (with pure strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ not efficient

Battle of the sexes

<table>
<thead>
<tr>
<th></th>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(0, 0)</td>
<td></td>
</tr>
</tbody>
</table>

⇒ not unique

Rock-Scisor-Paper

<table>
<thead>
<tr>
<th>1/2</th>
<th>P</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>(0, 0)</td>
<td>(1, -1)</td>
<td>(1, 1)</td>
</tr>
<tr>
<td>R</td>
<td>(-1, 1)</td>
<td>(0, 0)</td>
<td>(1, -1)</td>
</tr>
<tr>
<td>S</td>
<td>(1, -1)</td>
<td>(-1, 1)</td>
<td>(0, 0)</td>
</tr>
</tbody>
</table>

⇒ No equilibrium
**Definition: Mixed Strategy Nash Equilibria.**

A mixed strategy for player $i$ is a probability distribution over the set of pure strategies of player $i$.

An equilibrium in mixed strategies is a strategy profile $\sigma^*$ of mixed strategies such that:

$$\forall p, \forall \sigma_i, u_p(\sigma_{-p}^*, \sigma^*_p) \geq u_p(\sigma_{-p}^*, \sigma_p).$$

**Theorem 1.**

Any finite $n$-person noncooperative game has at least one equilibrium $n$-tuple of mixed strategies.
**Definition:** Mixed Strategy Nash Equilibria.

A mixed strategy for player $i$ is a probability distribution over the set of pure strategies of player $i$. An equilibrium in mixed strategies is a strategy profile $\sigma^*$ of mixed strategies such that: $\forall p, \forall \sigma_i, u_p(\sigma_{-i}^*, \sigma_p^*) \geq u_p(\sigma_{-i}^*, \sigma_p)$.

**Theorem 1.**

Any finite $n$-person noncooperative game has at least one equilibrium $n$-tuple of mixed strategies.

**Consequence:**

- The players mixed strategies are independent randomizations.
- In a finite game, $u_p(\sigma) = \sum_a \prod_{p'} \sigma_{p'}(a_{p'}) u_i(a)$.
- In a finite game, $\sigma^*$ is a Nash equilibrium iff $\forall a_i$ in the support of $\sigma_i^*$, $a_i$ is a best response to $\sigma_{-i}^*$. 
Find the Nash equilibria of these games (with mixed strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>
Mixed Nash Equilibria: Examples

Find the Nash equilibria of these games (with mixed strategies)

**The prisoner dilemma**

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ No strictly mixed equilibria

**Battle of the sexes**

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>

σ₁ = (2/3, 1/3), σ₂ = (1/3, 2/3)
Mixed Nash Equilibria: Examples

Find the Nash equilibria of these games (with mixed strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ No strictly mixed equilibria

Battle of the sexes

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>

σ₁ = (2/3, 1/3), σ₂ = (1/3, 2/3)

Rock-Scisor-Paper
Find the Nash equilibria of these games (with mixed strategies)

### The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ No strictly mixed equilibria

### Battle of the sexes

\[
\sigma_1 = \left(\frac{2}{3}, \frac{1}{3}\right), \quad \sigma_2 = \left(\frac{1}{3}, \frac{2}{3}\right)
\]

### Rock-Scisor-Paper

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
</tr>
<tr>
<td>R</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
</tr>
<tr>
<td>S</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
</tr>
</tbody>
</table>
Mixed Nash Equilibria: Examples

Find the Nash equilibria of these games (with mixed strategies)

The prisoner dilemma

<table>
<thead>
<tr>
<th></th>
<th>collaborate</th>
<th>deny</th>
</tr>
</thead>
<tbody>
<tr>
<td>collaborate</td>
<td>(1, 1)</td>
<td>(3, 0)</td>
</tr>
<tr>
<td>deny</td>
<td>(0, 3)</td>
<td>(2, 2)</td>
</tr>
</tbody>
</table>

⇒ No strictly mixed equilibria

Battle of the sexes

<table>
<thead>
<tr>
<th>Paul / Claire</th>
<th>Opera</th>
<th>Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opera</td>
<td>(2, 1)</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>Foot</td>
<td>(0, 0)</td>
<td>(1, 2)</td>
</tr>
</tbody>
</table>

\[ \sigma_1 = \frac{2}{3}, \frac{1}{3} \], \ \sigma_2 = \frac{1}{3}, \frac{2}{3} \)

Rock-Scisor-Paper

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
</tr>
<tr>
<td>R</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
<td>(1, −1)</td>
</tr>
<tr>
<td>S</td>
<td>(1, −1)</td>
<td>(−1, 1)</td>
<td>(0, 0)</td>
</tr>
</tbody>
</table>

\[ \sigma_1 = \sigma_2 = \frac{1}{3}, \frac{1}{3}, \frac{1}{3} \)
1 Individual Versus Collective Interest
   • Matrix Games - Nash Equilibria
   • Population Games - Wardrop Equilibria
   • Conclusion
   • Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   • Objective: Fair Sharing of Resources
   • Direct Method: Protocol Implementation
   • Indirect Method: Modifying the game

3 Conclusion
**Question:** A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

- 2 possible routes
- the needed time is a function of the number of cars on the road (congestion)
Question: A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take? The one with minimum cost

Cost of route "north":
\[10x + (x + 50) = 11x + 50\]

Cost of route "south":
\[(y + 50) + 10y = 11y + 50\]

Constraint:
\[x + y = 6\]

Conclusion? What if everyone makes the same reasoning? We get \(x = y = 3\) and everyone receives 83.
Question: A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take?
The one with minimum cost

Cost of route “north”:

\[10a + (x + 50) = 11x + 50\]

Cost of route “south”:

\[(y + 50) + 10y = 11y + 50\]

Constraint:

\[x + y = 6\]

Conclusion? What if everyone makes the same reasoning?

We get \[x = y = 3\] and everyone receives 83.
**Question:** A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take?
The one with minimum cost

**Cost of route “north”:**
\[ 10 \times x + (x + 50) = 11 \times x + 50 \]
Question: A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take?
The one with minimum cost

Cost of route “north”:
10 * x + (x + 50) = 11 * x + 50

Cost of route “south”:
**The Braess Paradox**

**Question:** A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take? The one with minimum cost

Cost of route “north”:

\[ 10 \times x + (x + 50) = 11 \times x + 50 \]

Cost of route “south”:

\[ (y + 50) + 10 \times y = 11 \times y + 50 \]
**Question:** A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take? The one with minimum cost

Cost of route “north”: 
\[10 \times x + (x + 50) = 11 \times x + 50\]

Cost of route “south”: 
\[(y + 50) + 10 \times y = 11 \times y + 50\]

Constraint: 
\[x + y = 6\]
**Question:** A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take? The one with minimum cost

Cost of route “north”:

\[ 10 \times x + (x + 50) = 11 \times x + 50 \]

Cost of route “south”:

\[ (y + 50) + 10 \times y = 11 \times y + 50 \]

Constraint: \( x + y = 6 \)

**Conclusion?** What if everyone makes the same reasoning?
The Braess Paradox

Question: A flow of users goes from A to B, with rate of 6 (thousands of people / sec). Each driver has two possible routes to go from A to B. Who takes which route?

Which route will one take?
The one with minimum cost
Cost of route “north”:
$$10 \times x + (x + 50) = 11 \times x + 50$$
Cost of route “south”:
$$(y + 50) + 10 \times y = 11 \times y + 50$$
Constraint: $$x + y = 6$$

Conclusion? What if everyone makes the same reasoning?
We get $$x = y = 3$$ and everyone receives 83
A new road is opened! What happens?

If no one takes it, it costs 70! so rational users will take it...

Cost of route "north":
\[10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z\]

Cost of route "south":
\[11 \times y + 50 + 10 \times z\]

Cost of "new" route:
\[10 \times x + 10 \times y + 21 \times z + 10\]

Conclusion?
We get
\[x = y = z = 2\]
and everyone gets a cost of 92!
A new road is opened! What happens?

If no one takes it, it cost is 

\[ \text{Cost of route "north":} \quad 11 \times (x + z) + (x + 50) = 11x + 50 + 10z \]

\[ \text{Cost of route "south":} \quad 11 \times y + 50 + 10z \]

\[ \text{Cost of "new" route:} \quad 10x + 10y + 21z + 10 \]

Conclusion?

We get \(x = y = z = 2\) and everyone gets a cost of 92!
The Braess Paradox

A new road is opened! What happens?

If noone takes it, it cost is 70! so rational users will take it... 😊

Cost of route "north":
\[10 \cdot a + (x + 50) = 11 \cdot x + 50 + 10 \cdot z\]

Cost of route "south":
\[11 \cdot y + 50 + 10 \cdot z\]

Cost of "new" route:
\[10 \cdot x + 10 \cdot y + 21 \cdot z + 10\]

Conclusion?
We get \(x = y = z = 2\) and everyone gets a cost of 92!
A new road is opened! What happens?

If noone takes it, it cost is 70! so rational users will take it... 😊

Cost of route “north”:

\[
\begin{align*}
\text{Cost of route “south”:} & \quad 11 \times y + 50 + 10 \times z \\
\text{Cost of “new” route:} & \quad 10 \times x + 10 \times y + 21 \times z + 10
\end{align*}
\]

Conclusion?

We get \( x = y = z = 2 \) and everyone gets a cost of 92!
A new road is opened! What happens?

If no one takes it, it cost is 70! so rational users will take it...

Cost of route “north”:
10 \times (x + z) + (x + 50) =
11 \times x + 50 + 10 \times z

Cost of route “south”:
11 \times y + 50 + 10 \times z

Conclusion?
We get \( x = y = z = 2 \) and everyone gets a cost of 92!
The Braess Paradox

A new road is opened! What happens?

If no one takes it, it costs 70! so rational users will take it...

Cost of route “north”:

\[ 10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z \]

Cost of route “south”:

Conclusion?

We get \( x = y = z = 2 \) and everyone gets a cost of 92!
A new road is opened! What happens?

If no one takes it, it cost is 70! so rational users will take it...

Cost of route “north”:
10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z

Cost of route “south”:
11 \times y + 50 + 10 \times z

Conclusion?
We get \( x = y = z = 2 \) and everyone gets a cost of 92!
A new road is opened! What happens?

If noone takes it, it cost is 70! so rational users will take it... 😊

Cost of route “north”:
$$10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z$$

Cost of route “south”:
$$11 \times y + 50 + 10 \times z$$

Cost of “new” route:
A new road is opened! What happens?

If noone takes it, it cost is 70! so rational users will take it... 😊

Cost of route “north”:
\[10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z\]

Cost of route “south”:
\[11 \times y + 50 + 10 \times z\]

Cost of “new” route:
\[10 \times x + 10 \times y + 21 \times z + 10\]
A new road is opened! What happens?

If no one takes it, it cost is 70! so rational users will take it... 😊

Cost of route “north”:
\[ 10 \times (x + z) + (x + 50) = 11 \times x + 50 + 10 \times z \]

Cost of route “south”:
\[ 11 \times y + 50 + 10 \times z \]

Cost of “new” route:
\[ 10 \times x + 10 \times y + 21 \times z + 10 \]

Conclusion?
We get \( x = y = z = 2 \) and everyone gets a cost of 92!
In the New York Times, 25 Dec., 1990, Page 38, What if They Closed 42d Street and Nobody Noticed?, By GINA KOLATA:

ON Earth Day this year, New York City’s Transportation Commissioner decided to close 42d Street, which as every New Yorker knows is always congested. ”Many predicted it would be doomsday,” said the Commissioner, Lucius J. Riccio. ”You didn’t need to be a rocket scientist or have a sophisticated computer queuing model to see that this could have been a major problem.” But to everyone’s surprise, Earth Day generated no historic traffic jam. Traffic flow actually improved when 42d Street was closed.
1. Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
     - Application: Performance Analysis

2. Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3. Conclusion
Efficiency versus (Individual) Stability

Prisoner Dilemma / Braess paradox show:

- Inherent conflict between individual interest and global interest
- Inherent conflict between stability and optimality

Typical problem in economy: free-market economy versus regulated economy.
Efficiency versus (Individual) Stability

Prisoner Dilemma / Braess paradox show:
▶ Inherent conflict between individual interest and global interest
▶ Inherent conflict between stability and optimality

Typical problem in economy: free-market economy versus regulated economy.

Suppose that you are a network operator. The different users compete to access the different system resources. Should you intervene?
▶ NO if the Nash Equilibria exhibit good performance
▶ YES otherwise
Efficiency versus (Individual) Stability

”Free-Market”: 

Suppose that you are a network operator. The different users compete to access the different system resources. Should you intervene?

▶ NO if the Nash Equilibria exhibit good performance
▶ YES otherwise
"Regulated Market":

Suppose that you are a network operator. The different users compete to access the different system resources. Should you intervene?

▶ NO if the Nash Equilibria exhibit good performance
▶ YES otherwise

"Regulated Market":

Corinne Touati (Inria)
Outline

1 Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3 Conclusion
Multiple applications execute concurrently on heterogeneous platforms and compete for CPU and network resources.

A fair sharing of resources amongst users is done at the system layer (network, OS).

We analyze the behavior of non-cooperative schedulers that maximize their own utility.

Master-worker platform:

Applications’ profiles:

Such applications are typical desktop grid applications (SETI@home, Einstein@Home, processing data of the Large Hadron Collider)....
A routing problem is a triplet:

- A graph \( G = (N, A) \) (the network)
- A set of flows \( d_k, k \in K \) and \( K \subset N \times N \) (user demands)
- latency functions \( \ell_a \) for each link

Theorem 2.

In networks with affine costs [Roughgarden & Tardos, 2002],

\[
C^{WE} \leq \frac{4}{3} C^{SO}.
\]

⇒ In affine routing, selfishness leads to a near optimal point.
Assessing the efficiency of equilibria
Example: Measuring the influence of information

Suppose that the system could be in 2 states $w_1$ and $w_2$, with probability $P(w_1) = P(w_2) = 1/2$.

<table>
<thead>
<tr>
<th>$(w_1)$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$(0, 0)$</td>
<td>$(6, -3)$</td>
</tr>
<tr>
<td>$b$</td>
<td>$(-3, 6)$</td>
<td>$(5, 5)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$(w_2)$</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$(-20, -20)$</td>
<td>$(-7, -16)$</td>
</tr>
<tr>
<td>$b$</td>
<td>$(-16, -7)$</td>
<td>$(-5, -5)$</td>
</tr>
</tbody>
</table>

What is the Nash Equilibria if:

- No player knows the system’s state:

- Both players are informed:

- Only player 1 knows:

Information can be detrimental!
Assessing the efficiency of equilibria
Example: Measuring the influence of information

Suppose that the system could be in 2 states $w_1$ and $w_2$, with probability $P(w_1) = P(w_2) = 1/2$.

<table>
<thead>
<tr>
<th>$w_1$</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>(0,0)</td>
<td>(6, -3)</td>
</tr>
<tr>
<td>b</td>
<td>(-3, 6)</td>
<td>(5, 5)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$w_2$</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>(-20, -20)</td>
<td>(-7, -16)</td>
</tr>
<tr>
<td>b</td>
<td>(-16, -7)</td>
<td>(-5, -5)</td>
</tr>
</tbody>
</table>

What is the Nash Equilibria if:

- No player knows the system’s state:
  EN: $(b, b)$, utility : $(0, 0)$

- Both players are informed:
  EN: $((a, a)|w_1), ((b, b)|w_2)$, utilité: $(-2.5, -2.5)$

- Only player 1 knows:
  EN: $((a, a)|w_1), ((b, a)|w_2)$, utilité $(-8, -3, 5)$

Information can be detrimental!
1. Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2. Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3. Conclusion
1 Individual Versus Collective Interest
   • Matrix Games - Nash Equilibria
   • Population Games - Wardrop Equilibria
   • Conclusion
   • Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   • Objective: Fair Sharing of Resources
   • Direct Method: Protocol Implementation
   • Indirect Method: Modifying the game

3 Conclusion
Bargaining Theory

- Aims at predicting the outcome of a bargain between 2 (or more) players
- The players are bargaining over a set of goods
- To each good is associated for each player a utility (for instance real valued)

Assumptions:

- Players have identical bargaining power
- Players have identical bargaining skills

Then, players will eventually agree on an point considered as “fair” for both of them.
Let $S$ be a feasible set, closed, convex, $(u^*, v^*)$ a point in this set, enforced if no agreement is reached.

A fair solution is a point $\phi(S, u^*, v^*)$ satisfying the set of axioms:

1. **(Individual Rationality)** $\phi(S, u^*, v^*) \geq (u^*, v^*)$ (componentwise)

2. **(Feasibility)** $\phi(S, u^*, v^*) \in S$

3. **(Pareto-Optimality)**
   \[ \forall (u,v) \in S, (u,v) \geq \phi(S, u^*, v^*) \rightarrow (u,v) = \phi(S, u^*, v^*) \]

4. **(Independence of Irrelevant Alternatives)**
   $\phi(S, u^*, v^*) \in T \subset S \Rightarrow \phi(S, u^*, v^*) = \phi(T, u^*, v^*)$

5. **(Independence of Linear Transformations)** Let
   \[ F(u,v) = (\alpha_1 u + \beta_1, \alpha_2 v + \beta_2), \; T = F(S), \; \text{then} \]
   \[ \phi(T, F(u^*, v^*)) = F(\phi(S, u^*, v^*)) \]

6. **(Symmetry)** If $S$ is such that $(u,v) \in S \Leftrightarrow (v,u) \in S$ and $u^* = v^*$ then $\phi(S, u^*, v^*) \overset{\text{def}}{=} (a,b)$ is such that $a = b$
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)$$

**Proof.**

**First case:** Positive quadrant  
**Second Case:** General case

right isosceles triangle
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)$$

**Proof.**

_First case:_ Positive quadrant  
_Second Case:_ General case

right isosceles triangle
Proposition: **Nash Bargaining Solution**

There is a unique solution function \( \phi \) satisfying all axioms:

\[
\phi(S, u^*, v^*) = \max_{u,v} (u - u^*) (v - v^*)
\]

**Proof.**

**First case:** Positive quadrant  
Right isosceles triangle  

**Second Case:** General case  

Pareto Feasability
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$
\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)
$$

**Proof.**

**First case:** Positive quadrant right isosceles triangle

**Second Case:** General case

right isosceles triangle
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v}(u - u^*)(v - v^*)$$

Proof.

**First case:** Positive quadrant

**Second Case:** General case

right isosceles triangle
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$
\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)
$$

**Proof.**

First case: Positive quadrant right isosceles triangle  
Second Case: General case
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)$$

**Proof.**

**First case:** Positive quadrant right isosceles triangle

**Second Case:** General case

---

- Feasability
- Symmetry
- Pareto
- Rationality
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)$$

**Proof.**

**First case:** Positive quadrant right isosceles triangle

**Second Case:** General case
Proposition: **Nash Bargaining Solution**

There is a unique solution function \( \phi \) satisfying all axioms:

\[
\phi(S, u^*, v^*) = \max_{u,v} (u - u^*)(v - v^*)
\]

**Proof.**

**First case:** Positive quadrant right isosceles triangle

**Second Case:** General case

**Feasability**

**Symmetry**

**Pareto**

**Ind. to Lin. Transf.**

\((u^*, v^*)\)
Proposition: **Nash Bargaining Solution**

There is a unique solution function $\phi$ satisfying all axioms:

$$\phi(S, u^*, v^*) = \max_{u,v} (u - u^*) (v - v^*)$$

**Proof.**

**First case:** Positive quadrant right isosceles triangle

**Second Case:** General case
Axiomatic Definition VS Optimization Problem

- Individual Rationality
- Feasibility
- Pareto-Optimality
- Independence of Linear Transformations
- Symmetry
Axiomatic Definition VS Optimization Problem

1. Individual Rationality
2. Feasibility
3. Pareto-Optimality
4. Independence of Linear Transformations
5. Symmetry
6. Dependend to irrelevant alternatives Nash (NBS) / Proportional Fairness $\prod (u_i - u_i^d)$

+ 

4. Monotony
   - Raiffa-Kalai-Smorodinsky / max-min
   - Recursively $\max \{u_i | \forall j, u_i \leq u_j\}$
4. Inverse Monotony
   - Thomson / global Optimum (Social welfare)
   - $\max \sum u_i$
Outline

1 Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3 Conclusion
Imagine a system with:

- \( n \) individual users aiming at optimizing their throughput \( x_n \)
- A routing matrix \( A \) giving the set of paths followed by each connection: \( A_{i,j} = \begin{cases} 1 & \text{if connection } i \text{ uses link } j \\ 0 & \text{otherwise} \end{cases} \)
- Capacity constraints on each link \( C_{\ell} \)
- What is the Nash equilibrium of the game? What protocol does it correspond to?
- How can we implement fairness in a distributed way?
Example: A simple network with 3 links

\[ n_{0\rightarrow2} = 2, \ n_{1\rightarrow2} = 3, \ n_{2\rightarrow3} = 4 \]

Throughput of flow \( i \):

\[ \frac{\lambda_i \cdot \text{capa}}{\lambda_1 + \lambda_2} \]
Hypothesis:

Ring topology network, \( N \) identical links with capacity \( C \).
Source \( i \) uses links \( i \) and \( i + 1 \) (mod \( N \))

Link equations:

\[
\begin{align*}
\lambda_2' &= \frac{\lambda_2 C}{\lambda_2 + \lambda_1'} = \frac{C}{1 + \lambda_1'/\lambda_2} \\
\lambda_2'' &= \frac{\lambda_2' C}{\lambda_3 + \lambda_2'} = \frac{C^2}{\lambda_3 (1 + \lambda_1'/\lambda_2)}
\end{align*}
\]
Hypothesis $\lambda \gg C$

Exit throughput of flow $i$:

$$\lambda'' = \frac{C^2}{C + \lambda(1 + \lambda'/\lambda)}, \quad \text{and}$$

$$\frac{\lambda'}{\lambda} = \frac{1}{2} \left( \sqrt{1 + \frac{4C}{\lambda}} - 1 \right) \sim \frac{C}{\lambda}$$

Then $\lambda'' \sim \frac{C^2}{\lambda}$
The Flow Control Problem:
The Non Cooperative Game

This is network collapse:

- The network is full
- Little or no useful information is going through (here
  \[ \lambda'' \sim \frac{C^2}{\lambda} \rightarrow_{\lambda \rightarrow \infty} 0 \])

Observed in 1984 (cf RFC 896) with TCP flows: the protocol detects a loss, so it retransmits the packet, hence increasing its incoming throughput...

Since then a flow control mechanism has been implemented in TCP 😊

Why hadn’t we observe this kind of phenomena before with telephony?
The Optimal Flow Problem

- **$N$ individual users** aiming at optimizing their throughput $x_n$
- **A routing matrix $A$** giving the set of paths followed by each connection: $A_{i,j} = \begin{cases} 1 & \text{if connection } i \text{ uses link } j \\ 0 & \text{otherwise} \end{cases}$
- **Capacity constraints** on each link $C_\ell$
- **User utility function** $f_n : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ that are increasing and strictly concave.

The flow control problem is:

$$\max_{x} \sum_{n} f_n(x_n) \quad \text{s.t.} \quad \forall \ell, (Ax)_\ell - C_\ell \leq 0 \text{ and } x \geq 0$$
Example: The Flow Control Problem

4 connections / 3 links.

\[ x_1 + x_0 \leq 1, \]
\[ x_2 + x_0 \leq 1, \]
\[ x_3 + x_0 \leq 1. \]

\[ \Rightarrow 4 \text{ variables and 3 (in)equalities.} \]

How to choose \( x_0 \) among the Pareto optimal points?

(Nota: in this case the utility set is the same as the strategy set)
Example: The Flow Control Problem

4 connections / 3 links.

\[
\begin{align*}
  x_1 + x_0 & \leq 1, \\
  x_2 + x_0 & \leq 1, \\
  x_3 + x_0 & \leq 1.
\end{align*}
\]

\(\Rightarrow\) 4 variables and 3 (in)equalities.

How to choose \(x_0\) among the Pareto optimal points?

- **Max-Min fairness**
  \[
  \begin{align*}
  x_0 &= 0.5, \\
  x_1 &= x_2 = x_3 = 0.5
  \end{align*}
  \]

- **Social Optimum**
  \[
  \begin{align*}
  x_0 &= 0, \\
  x_1 &= x_2 = x_3 = 1
  \end{align*}
  \]

- **Proportionnal Fairness**
  \[
  \begin{align*}
  x_0 &= 0.25, \\
  x_1 &= x_2 = x_3 = 0.75
  \end{align*}
  \]

(Nota: in this case the utility set is the same as the strategy set)
The Optimal Flow Problem

- \( N \) individual users aiming at optimizing their throughput \( x_n \)
- A routing matrix \( A \) giving the set of paths followed by each connection: \( A_{i,j} = \begin{cases} 1 & \text{if connection } i \text{ uses link } j \\ 0 & \text{otherwise} \end{cases} \)
- Capacity constraints on each link \( C_\ell \)
- User utility function \( f_n : \mathbb{R}^+ \to \mathbb{R}^+ \) that are increasing and strictly concave.

The flow control problem is:

\[
\max_x \sum_n f_n(x_n) \quad \text{s.t.} \quad \forall \ell, (Ax)_\ell - C_\ell \leq 0 \text{ and } x \geq 0
\]

How to (efficiently and in a distributed manner) solve this?
Flow control algorithm: AIMD (Additive Increase Multiplicative Decrease)

- Window $w_n$: number of packets of a connection that can be outstanding at any time (i.e. for which no ack has been received yet)
- The Round Trip Time (RTT$_n$) of connection $n$ (supposed independant of the load)
- Additive increase: at each RTT, increase the window size by 1 if there is no mark
- Multiplicative decrease: at each marked packet, halve the window size
Flow control algorithm: AIMD (Additive Increase Multiplicative Decrease)

- Source rate: \( x_n(t) = \frac{w_n(t)}{RTT_n} \)

- Loss probability: \( q_n = 1 - \prod_{\ell,A_n,\ell=1} (1 - p_\ell) \approx \sum_{\ell,A_n,\ell=1} p_\ell \)

- Between two packet emissions:

\[
\Delta t \approx \frac{1}{x_n(t)} = \frac{RTT_n}{w_n(t)}
\]

\[
w_n(t + \Delta t) - w_n(t) \approx \frac{1}{w_n(t)} (1 - q_n(t)) - \frac{w_n(t)}{2} q_n(t)
\]

\[\Rightarrow \frac{dx_n}{dt}(t) = \frac{1 - q_n(t)}{RTT_n^2} - \frac{1}{2} q_n(t)x_n^2(t)\]
Hence, the AIMD flow control of TCP follows dynamics:

\[
\frac{dx_n}{dt}(t) = \frac{1 - q_n(t)}{\text{RTT}_n^2} - \frac{1}{2} q_n(t) x_n^2(t)
\]

Using tools from control theory (Lyapunov function), one can establish that it maximizes over \( x \) function

\[
W(x) = \sum_n \sqrt{2} \frac{\text{RTT}_n}{\text{RTT}_n^2} \text{atan} \left( \frac{x_n \text{RTT}_n}{\sqrt{2}} \right) - \sum_\ell \int_0^\infty \sum_m A_{m,\ell} x_m p_\ell(y) dy
\]

Utility \( f_n(x_n) \) link cost \( LC_\ell \)
Hence, the AIMD flow control of TCP follows dynamics:

\[
\frac{dx_n}{dt}(t) = \frac{1 - q_n(t)}{\text{RTT}_n^2} - \frac{1}{2} q_n(t)x_n^2(t)
\]

Using tools from control theory (Lyapunov function), one can establish that it maximizes over \( x \) function

\[
W(x) = \sum_n \left( \sqrt{2} \text{atan} \left( \frac{x_n \text{RTT}_n}{\sqrt{2}} \right) \right) - \sum \left( \sum_m A_{m,\ell} x_m \right) \int_0 \left( p_{\ell}(y) dy \right)
\]

Utility \( f_n(x_n) \)

Link cost \( \text{LC}_\ell \)
Outline

1 Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3 Conclusion
Application: The Optimal Association Problem

Mobile Base station

Base station
Application: The Optimal Association Problem

Mobile

Base station
Application: The Optimal Association Problem

Diagram showing the association between a mobile device and a base station.
Application: The Optimal Association Problem

Diagram:
- Mobile
- Base station

Corinne Touati (Inria)
**Context**

- The cells of different technologies overlap (LTE, WiFi, Wimax, etc).
- Mobiles are multi-technology compatible.
- Protocols:
  - Multi-homing: having several connections active at once
  - Vertical Handover: to switch from one technology to another

**Goal**

Find an association algorithm between mobiles and base stations that is:
- distributed
- optimal
A set $\mathcal{N}$ of mobiles.

A set $\mathcal{I}_n$ of Base Stations (BS) that $n \in \mathcal{N}$ can connect to.

$s_n \in \mathcal{I}_n$ choice of mobile $n$.

$\ell^i$: load (vector) of BS $i$: $\ell^i_n = \begin{cases} 1 & \text{if } s_n = 1 \\ 0 & \text{else.} \end{cases}$

$u_n(\ell^i)$: throughput of mobile $n$ given the load of cell $i$. 
Game Formulation

- A set $\mathcal{N}$ of mobiles.
- A set $\mathcal{I}_n$ of Base Stations (BS) that $n \in \mathcal{N}$ can connect to.
- $s_n \in \mathcal{I}_n$ choice of mobile $n$.
- $\ell^i$: load (vector) of BS $i$: $\ell^i_n = \begin{cases} 1 & \text{if } s_n = 1 \\ 0 & \text{else.} \end{cases}$
- $u_n(\ell^i)$: throughput of mobile $n$ given the load of cell $i$.

Association game. 

$(\mathcal{N}, \mathcal{I}, \mathcal{U})$
How to design games so as to serve one’s purpose is the object of mechanism design.
Step 1: Creating Fake Games

Original Game. \((\mathcal{N}, \mathcal{I}, \mathcal{U})\)

New Game. \((\mathcal{N}, \mathcal{I}, \mathcal{R})\)

**Fairness**

Definition: "repercussion utility".

\[
 r_n(\ell^{s_n}) = f_n(u_n(\ell^{s_n})) - \sum_{m \neq n: s_m = s_n} f_m(u_m(\ell^{s_n} - e_n)) - f_m(u_m(\ell^{s_n}))
\]

Simple computation done by the BS.

How to design games so as to serve one’s purpose is the object of mechanism design.
Step 2: Choosing a dynamics converging to the Nash equilibria

1. We switch to mixed strategies:

- \( q_{n,i} \) \( \overset{\text{def}}{=} \mathbb{P}[s_n = i] \).
- \( q_n = (q_{n,i})_{i \in \mathcal{I}_n} \): strategy of mobile \( n \).

2. We choose the replicator dynamics:

\[
\frac{dq_{n,i}}{dt} = q_{n,i}(\bar{u}_{n,i}(q) - \sum_{j \in \mathcal{I}_n} q_{n,j} \bar{u}_{n,j}(q)).
\]

Theorem: (in potential games):
- The replicator dynamics converges to a set of Nash equilibria.
- Objective function is increasing along the trajectories (Lyapunov function).
Step 3: Deriving a distributed algorithm

**Algorithm: stochastic approximation of the replicator dynamics**

For all \( n \in \mathcal{N} \):

- Choose initial strategy \( q_n(0) \).

- At each time epoch \( t \):
  - Choose \( s_n \) according to \( q_n(t) \).
  - Update:
    \[
    q_n(t + 1) = q_n(t) + \varepsilon r_n(\ell^{s_n}(s)) \left( I_{s_n = i} - q_{n,i}(t) \right).
    \]

- Simple computation for the mobile.
Evolution of one user’s strategy that can connect to 5 cells.
Arrivals and departures: evolution of the global throughput with white Gaussian noise.
Outline

1 Individual Versus Collective Interest
   - Matrix Games - Nash Equilibria
   - Population Games - Wardrop Equilibria
   - Conclusion
   - Application: Performance Analysis

2 Designing Efficient Control Mechanisms
   - Objective: Fair Sharing of Resources
   - Direct Method: Protocol Implementation
   - Indirect Method: Modifying the game

3 Conclusion
Résumé

Jeux : situations de décisions interactives dans lesquelles l’utilité (bien-être) de chaque individu dépend des décisions des autres.

Théorie des jeux : théorie de la décision (rationnelle) d’agents stratégiquement interdépendants

<table>
<thead>
<tr>
<th>Jeux coopératifs</th>
<th>Jeux Non-cooperatifs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vision globale</td>
<td>Comportement individuel</td>
</tr>
<tr>
<td>consensus efficace et équitable</td>
<td>converge (ou non) vers un équilibre</td>
</tr>
</tbody>
</table>

Mécanismes:

researchère de règles du jeu pour obtenir des comportements satisfaissants.
Nous n’avons fait qu’effleurer la surface...

Il existe bien d’autres modèles de jeux:

▶ **Jeux répétés**: on rejoue plusieurs fois le même jeu (ex. le tarot en 100 points). Le but est d’alors maximiser le revenu moyen.

▶ **Jeux dynamiques**: les joueurs jouent à tour de rôle. L’ensemble des stratégies dépend alors des étapes précédentes du jeu.

▶ **Jeux évolutionnaires**: inspiré des approches Darwinistes. Se compose d’un jeu interne (entre les individus) et d’un jeu externe (le processus évolutionnaire).

▶ **Jeux stochastiques**: jeu dynamique (=évoluant dans le temps) dans lequel les transitions sont probabilistes: le nouvel état est déterminé par une distribution de probabilité dépendant de l’état courant et des actions choisies (Markov Decision Process).

▶ **Équilibres de Stackelberg**: jeu entre deux joueurs aux rôles asymétriques: un meneur et un suiveur (utilisé par exemple dans les mécanismes de tarification des e-services). Autres modèles liés: compétition de Bertrand, compétition de Cournot.
Other hot topics in game theory

- **Mechanism design**: how to design rules of a game so as to achieve a specific outcome, even though each player is selfish.

- **Auctions**: resource allocation in P2P, frequency allocation in wireless.


- **Fair division or cake cutting problem**: how to divide resource such that all recipients believe that they have received their fair share.

- **Election**: Plurality voting systems are not necessarily fair.

- **Stable marriages**: Problem of finding a matching.

- **Super-modular games**: utility functions are such that higher choices by one player make one’s own strategy higher look relatively more desirable.

- **Games with incomplete information or Bayesian games**: some player have private information about something relevant to their decision making.

- **Games with imperfect information**: players do not perfectly observe the actions of other players.